LD PUMPED FIBRE AMPLIFIER WITH SECOND RESONATOR OR INPUT SIGNAL FOR GAIN LIMITATION

Field of Invention

This invention relates to an apparatus for providing optical radiation. The invention has particular relevance for high-power fibre lasers, and for welding, drilling, cutting and marking applications.

Background to the Invention

Fibre lasers are increasingly being used for material processing applications such as welding, cutting and marking. Their advantages include high efficiency, robustness and high beam quality.

Traditional lasers used for material processing applications predominate at around 1.06μm and longer wavelengths such as provided by a carbon dioxide laser (10.6μm). These lasers are being supplemented by fibre lasers operating at around 1.06μm.

High power fibre lasers and amplifiers are also finding application in coherent combining systems, in which the output from parallel lasers or amplifiers are coherently combined together. These systems are either based on parallel master oscillator power amplifiers driven from a common source such as a distributed feedback laser, or use parallel lasers and rely on feedback to phase lock the lasers together.

High power fibre lasers are often single mode and are often pumped at high intensity levels. If insufficient optical power is provided to saturate the gain medium, very high inversion levels can result in giant pulse generation, often referred to as "self Q-switching". The result can be catastrophic failure of the optical fibre gain medium, pump diodes and other optical components within the laser because the

generated giant pulse is of such high intensity or contains so much optical energy that it can destroy the components. Voids can appear along the cores of optical fibres, laser diodes can be damaged such that they no longer emit optical radiation, and optical surfaces can be damaged. Such failures can be a particular problem with high-power Q-switched lasers, because these contain an amplifier that is designed to store energy when the Q-switch is open, and to release the energy in the form of a pulse when the Q-switch is closed. If the Q-switch is not closed often enough, or if a laser cavity is not formed when the Q-switch is closed through misalignment or other failure, then large amounts of stored energy can be built up within the amplifier which can be released through a self Q-switching or other mechanism resulting in a giant pulse of sufficient energy to damage the amplifier. Failures can also be a problem with master oscillator power amplifiers. If the power amplifier is operated without an input signal, then the amplifier will store optical energy which can be released in a giant pulse that destroys optical components within the power amplifier. The failure can also be a problem for material processing systems that require very high reliability for 24 hour 7 days per week operation. Even though self Q-switching events may be very rare, it would be altogether better to ensure that the amplifiers are unable to release stored energy in a manner that would destroy the product.

An aim of the present invention is to provide apparatus for providing optical radiation that reduces the above aforementioned problem.

Summary of the Invention

According to a non-limiting embodiment of the present invention, there is provided apparatus for providing optical radiation having a signal wavelength, which apparatus comprises at least one pump for providing pump radiation, a gain medium,

and energy limiting means, in which the pump radiation acts on the gain medium to provide stored energy and gain for optical amplification, characterised in that the gain has a maximum gain at a wavelength at which the maximum gain occurs, and the energy limiting means limits the maximum gain and the amount of stored energy that is able to be stored to values below those at which the stored energy will cause damage to the apparatus.

The stored energy and gain in apparatus for providing optical radiation having a signal wavelength, for example an optical amplifier or a laser, arise from the inversion of the gain medium when pumped by the pump. In the absence of an input signal, the gain medium can become heavily inverted leading to large amounts of stored energy and optical gain. Without use of the energy limiting means, the available gain at small intensities of the input signal can be so large that a very small perturbation at the input could extract a significant amount of stored energy in a single or few passes to a level that can damage the apparatus. For example, in a ytterbium-doped fibre amplifier, a 1ns input pulse arising out of noise that is allowed to extract 1mJ of stored energy will provide an output pulse having 1MW of optical power, more than is sufficient to damage the optical fibre for example by creating voids in its core. The energy limiting means of the present invention ensures that the stored energy and gain are such that the stored energy is unable to be released in a way that would damage the apparatus.

The gain medium may be such that the signal wavelength and the wavelength at which the maximum gain occurs are separated by less than 10nm. This is preferred to make optimal use of the maximum gain in that the energy limiting means has to do less work in order to ensure that the stored energy is unable to damage the apparatus. Alternatively, the gain medium may be such that the signal wavelength and the

wavelength at which the maximum gain occurs are separated by at least 10nm. In this case, it is preferred that the energy limiting means operates around the maximum gain.

According to a first embodiment of the present invention, the energy limiting means comprises first and second reflectors characterised by first and second reflectivities and an energy limiting wavelength, the first and second reflectors forming a cavity about the gain medium, and the first and second reflectors being such that they limit the available gain when the gain medium is pumped by the pump such that the stored energy is unable to cause damage to the apparatus.

The first reflectivity may be greater, the same as, or less than the second reflectivity. At least one of the first and second reflectors may be designed to reflect at least 0.01% of optical radiation at the energy limiting wavelength.

The product of the first and second reflectivities may be substantially equal to the reciprocal of twice the small signal gain at the energy limiting wavelength.

The apparatus may be such that the gain medium is pumped by at least 1W of the pump radiation, and the maximum gain may be less than 40dB.

The gain medium may be pumped by at least 10W of the pump radiation, and the maximum gain may be less than 30dB.

The gain medium may be pumped by at least 100W of the pump radiation, and the maximum gain may be less than 25dB.

The gain medium may be pumped by at least 1000W of the pump radiation, and the maximum gain may be less than 20dB.

According to a second embodiment of the present invention, the gain medium is pumped by the pump radiation at a pump power of at least 1W, and in which the energy limiting means comprises an optical source that provides at an energy limiting

wavelength an energy limiting power greater than -40dB relative to the pump power, which energy limiting power acts on the gain medium to reduce the amount of stored energy and gain when the gain medium is pumped by the pump such that the stored energy is unable to cause damage to the apparatus.

The gain medium may be pumped by at least 10W of the pump power, and the energy limiting source may provide an energy limiting power greater than -30dB relative to the pump power.

The gain medium may be pumped by at least 100W of the pump power, and the energy limiting source may provide an energy limiting power greater than -25dB relative to the pump power.

The gain medium may be pumped by at least 1000W of the pump power, and the energy limiting source may provide an energy limiting power greater than -20dB relative to the pump power.

In the first and second embodiments, the energy limiting wavelength may be in the same emission band as the signal wavelength. Alternatively the energy limiting wavelength may be in a different emission band from the signal wavelength. The energy limiting wavelength may be greater than the signal wavelength. Alternatively, the energy limiting wavelength may be less than the signal wavelength.

The energy limiting wavelength and the wavelength at which the maximum gain occurs may be separated by less than 10nm. This is preferable in order to reduce the amount of energy limiting signal. Alternatively, the energy limiting wavelength and the wavelength at which the maximum gain occurs may be separated by at least 10nm which facilitates filter the energy limiting signal from the output radiation.

In all embodiments of the invention, the apparatus may include a scanner into which the optical radiation is coupled. The apparatus may include a controller for

synchronizing the optical radiation with the scanner. Such apparatus is useful for material processing applications such as welding, cutting, brazing and drilling.

In all embodiments of the invention, the gain medium may form part of an optical fibre. The optical fibre may comprise rare-earth dopant.

The optical fibre may be a cladding pumped optical fibre comprising a core, an inner cladding for guiding pump radiation supplied by the pump, and an outer cladding, and in which the rare earth dopant is disposed in at least one of the core and the inner cladding.

The rare-earth dopant may be selected from the group comprising Ytterbium, Erbium, Neodymium, Praseodymium, Thulium, Samarium, Holmium and Dysprosium, Erbium codoped with Ytterbium, or Neodymium codoped with Ytterbium.

The apparatus may be in the form of an amplifier, a laser, a master oscillator power amplifier, a Q-switched laser, a source of amplified spontaneous emission, or a continuous wave laser.

The apparatus may be in the form of a laser for material processing.

Brief Description of the Drawings

Embodiments of the invention will now be described solely by way of example and with reference to the accompanying drawings in which:

Figure 1 shows apparatus for providing optical radiation according to the present invention;

Figure 2 shows apparatus in the form of a Q-switched laser;

Figure 3 shows the variation of inversion with time in a Q-switched laser;

Figure 4 shows the optical output of a Q-switched laser;

Figure 5 shows the output of the energy limiting means with time;

Figure 6 shows variation of inversion with time in a Q-switched laser that has been gain clamped;

Figures 7 shows the optical output of a Q-switched laser that has been gain clampled;

Figure 8 shows the output of the energy limiting means with time from a Q-switched laser that has been gain clamped;

Figure 9 shows apparatus in the form of a Q-switched laser in which the energy limiting means comprises an optical source;

Figure 10 shows apparatus in the form of a master oscillator power amplifier;

Figure 11 shows apparatus in the form of an optical amplifier that comprises a cavity;

Figure 12 shows apparatus in the form of an optical amplifier that comprises an optical source;

Figure 13 shows apparatus in the form of a master oscillator power amplifier;

Figure 14 shows apparatus in the form of a material processing system comprising a plurality of seed lasers

Figure 15 shows an amplifier that is gain clamped with two fibre Bragg gratings;

Figure 16 shows the gain as a function of pump power measured in the amplifier of Figure 15;

Figure 17 shows optical spectra measured at the output of the amplifier of Figure 15;

Figure 18 shows the gain of the amplifier measured with different fibre Bragg gratings;

Figure 19 shows the gain spectra measured as a function of wavelength;

Figure 20 shows gain and grating reflectivity design curves;

Figures 21, 23, and 25 show gains for amplifiers with and without energy limiting power for various levels of pump power; and

Figures 22, 24, and 26 show small signal gains as a function of wavelength corresponding to the amplifiers of Figures 21, 23 and 25.

Detailed Description of Preferred Embodiments of the Invention

With reference to Figure 1, there is provided apparatus 10 for providing optical radiation 3 having a signal wavelength λ_s 4, which apparatus 10 comprises at least one pump 5 for providing pump radiation 15, a gain medium 6, and energy limiting means 2, in which the pump radiation 15 acts on the gain medium 6 to provide stored energy 7 and gain 8 for optical amplification, characterised in that the gain 8 has a maximum gain 14 at a wavelength 18 at which the maximum gain 14 occurs, and the energy limiting means 2 limits the maximum gain 14 and the amount of stored energy 7 that is able to be stored to values below those at which the stored energy 7 will cause damage to the apparatus 10. Figure 1 shows the gain medium 6 and the pump 5 being part of a first amplifier 1. The gain 8 is shown over an emission band 9 as a function of wavelength 12. The signal wavelength λ_s 4 is preferably within the emission band 9. The energy limiting means 2 can be a part of the first amplifier 1 or be provided externally to the first amplifier 1.

Figure 2 shows apparatus in the form of a Q-switched laser 20 which contains the first amplifier 1 and the energy limiting means 2. The first amplifier 1 is an optical fibre amplifier comprising a pump 5 and a pump coupler 22. The gain medium 6 is provided by a rare-earth doped fibre 23. The pump 5 can be a fibre

laser, a semiconductor laser diode, a laser diode bar, a laser diode stack, or a module comprising a plurality of semiconductor laser diodes, bars or stacks. The rare-earth doped fibre 23 can comprise an optical fibre doped with ytterbium, erbium, thulium, neodymium or holmium, or co-doped with one or more of these rare-earth ions, such optical fibre being operated as a two, three or four level laser system. The pump coupler 22 can be an optical coupler. Alternatively, the pump coupler 22 can comprise one of the many optical arrangements used to core pump or cladding pump rare-earth doped fibres such as the rare-earth doped fibre 23. Such optical arrangements include using V-grooves etched or machined into the fibre 23, side pumping via another optical fibre, or using dichroic mirrors. The Q-switched laser 20 also comprises an optical switch 24, and third and fourth reflectors 25, 26. The optical switch 24 is shown as an acousto-optic modulator in Figure 2, but can be a Q-switch comprising a Pockels cell, a Kerr cell. Alternatively, the optical switch 24 can be an electo-optic switch such as one made from lithium niobate. The third and fourth reflectors 25, 26 can be gratings, fibre Bragg gratings, dichroic mirrors, or other reflectors commonly used in waveguide lasers.

The energy limiting means 2 comprises a first cavity 27. The first cavity 27 is formed by first and second reflectors 281, 282 characterised by first and second reflectivities 283, 284 and an energy limiting wavelength λ_l 285. The first and second reflectors 281, 282 are such that they limit the maximum gain 14 when the rare-earth doped fibre 23 is pumped by the pump 5. This is achieved by configuring the first cavity 27 to lase by appropriate selection of the first and second reflectors 281, 282 in order to generate an energy limiting signal 29 at the energy limiting wavelength λ_l 285. The energy limiting wavelength 285 is preferably a different wavelength than the signal wavelength λ_s 4. The first cavity 27 will in general emit part of the energy

limiting signal 29 through the first and second reflectors 281, 282. The first and second reflectors 281, 282 can be gratings, fibre Bragg gratings, dichroic mirrors, or other reflectors commonly used in waveguide lasers. The functions of the second reflector 282 and the fourth reflector 26 can be combined in a single reflector that reflects at both the signal wavelength λ_s 4 and the energy limiting wavelength λ_l 285

Figure 3 shows the inversion 33 N of the rare-earth doped fibre 23 as a function of time 34 during low-power operation. (Note that more exactly, Figure 3 shows some form of average inversion 33 as the inversion may vary along the length of the rare-earth doped fibre 23). The higher the inversion 33, the more the stored energy 7, and the higher the gain 8. Four inversions are shown, namely a maximum inversion 30 Nmax, a first cavity inversion 31 Nc, a Q-switched threshold inversion 32 Nthr, and an inversion 35. The maximum inversion 30 Nmax corresponds to the maximum inversion that can be achieved by pumping the Q-switched laser 20 with the pump 5 with the switch OFF and with no feedback from reflector 25 and without the presence of the first cavity 27. Figure 3 shows the inversion 33 reaching the maximum inversion 30 by the dotted line 39. The first cavity threshold inversion 31 Nc corresponds to the first threshold, namely the threshold of a laser formed by the first cavity 27. The Q-switched threshold inversion 32 Nthr corresponds to the Q-switched threshold, namely the average threshold for the Q-switched laser 20 at a given pulse repetition rate. The inversion 35 corresponds to the inversion N_d within the Q-switched laser at which optical damage occurs within the apparatus, namely the optical damage intensity 72 which is described with reference to Figure 7.

Figure 4 shows the optical power 45 Ps of the optical radiation 3 from the Q-switched laser 20. The optical power 45 comprises a plurality of pulses 40 that are triggered by closing the optical switch 24. Figure 5 shows the optical power 50 Pc of

the energy limiting signal 29 with time t 34 (in this case the first cavity 27). The output power 50 is zero because the inversion 33 never reaches the first cavity threshold inversion 31 Nc.

Figure 6 shows the inversion 33 for the Q-switched laser 20 achieved for either higher power pumping or lower repetition rate. The inversion 33 is clamped periodically at the first cavity threshold inversion 31 Nc. When the optical switch 24 is turned on, the Q-switched laser 20 emits the pulses 70 shown in Figure 7, and the inversion 33 falls. The pulses 70 have a peak intensity 71. Figure 8 shows the output 50 of the energy limiting means 2 (in this case the first cavity 27) which comprises pulses 80 which occur when the inversion 33 has reached the first cavity threshold inversion 31 Nc.

The presence of the first cavity 27 within the Q-switched laser 20 can be seen to have limited the inversion 33 and hence the peak intensity 71 of the optical radiation 3. This is especially useful for high-power applications for limiting the intensity 71 of the optical radiation 3 such that it is below the optical damage intensity 72 of the apparatus. By optical damage intensity 72, it is meant the intensity of the optical radiation 3 at which optical damage occurs at some location within the apparatus. This aspect of the invention relies upon the first threshold inversion 31 being higher than the Q-switched threshold inversion 32, and the inversion 35 shown with reference to Figures 3 and 6 corresponding to the optical damage intensity 72 being higher than the first threshold 31. By high-power applications it is meant applications in which the intensity of the optical radiation 3 within the optical fibre 23 approaches or exceeds the optical damage thresholds of the components within the apparatus. Experimentally, optical damage has been observed in silica optical fibres at intensities above 1GW/cm^2, and the apparatus is believed to be very useful for

intensities above 1GW/ cm^2 and even more so for intensities above 5GW/cm^2. In typical single mode laser systems, these intensities can correspond to pulse energies greater than 0.1mJ and 0.5mJ respectively, and average output powers greater than around 1W and 5W respectively. For multimode lasers, the pulse energies and optical powers are even higher, the approximate threshold values being calculated from the cross-sectional area of the cores. Other components that can be damaged by high intensity include laser diodes, lenses, fibres such as beam delivery fibres, mirrors, and beam combiners.

Figure 9 shows apparatus in the form of a Q-switched laser 90 in which the energy limiting means 2 comprises an energy limiting source 91 and a coupler 92. The energy limiting source 91 provides energy limiting power 94 at an energy limiting wavelength λ_l 285 which acts on the rare-earth doped fibre 23 to reduce the amount of stored energy 7 and gain 8 when the rare-earth doped fibre 23 is pumped by the pump 5.

The energy limiting source 91 can be a laser diode, distributed feedback laser diode, a distributed Bragg reflector laser diode, or a fibre laser. The coupler 92 may be an optical coupler, a wavelength division multiplexing coupler, an optical tap (used in reverse), a polarisation beam splitter, or a dichroic mirror. The energy limiting wavelength λ_l 285 must be different from the signal wavelength λ_s 4. The energy limiting power 94 is selected to prevent the inversion 33 of the first amplifier 1 from reaching the first threshold 31 Nc (shown with reference to Figure 3). The energy limiting source 91 can be operated continuous wave, modulated, or pulsed. However it is important that the energy limiting source 91 is clamping the Q-switched laser to prevent the inversion 33 reaching the inversion 35 corresponding to the optical damage intensity 72 (shown with reference to Figure 7).

Figure 10 shows apparatus in the form of a master oscillator power amplifier 100 comprising a seed laser 101, an optional isolator 102, and an optical amplifier 103. The seed laser 101 comprises the energy limiting means 2. The seed laser 101 can be the Q-switched laser 20 with the optical output 50 being used to clamp the inversion of the optical amplifier 103. The seed laser 101 can also be the Q-switched laser 90 with the energy limiting source 91 configured such that its output 94 is configured to co-propagate with the output radiation 3 rather than counter propagate as shown in Figure 9. The isolator 102 can be an optical isolator, an optical circulator, a polariser, an optical switch, an acousto-optical modulator, or an electro-optic modulator such as a Pockels cell or Kerr shutter.

Figure 11 shows apparatus in the form of an amplifier 110 configured to amplify an optical signal 113 having an input power P_{in} 115 at the signal wavelength λ_s 4. The energy limiting means 2 comprises a cavity 112. The cavity 112 clamps the inversion of the optical fibre 23 in a similar way as described with reference to Figures 2 and 4. The amplifier 110 may be used to replace the amplifier 103 in Figure 10.

Figure 12 shows apparatus in the form of an amplifier 121 in which the gain medium 6 is provided by the rare-earth doped fibre 23. Two pumps 5 are provided to pump the rare-earth doped fibre 23. The energy limiting means 2 comprises the energy limiting source 91 and the coupler 92. The energy limiting means 2 delivers the energy limiting power 94 at the energy limiting wavelength λ_l 285 to the rare-earth doped fibre 23. The energy limiting power 94 clamps the inversion of the optical fibre 23 in a similar way as described with reference to Figure 9 in order to limit the inversion 33 of the rare-earth doped fibre 23, and in particular the amount of

stored energy 7 and gain 8 such that the stored energy 7 is unable to damage the amplifier 121.

The amplifiers 110 and 120 are useful for high-power and high-energy applications (>1W continuous wave or >0.1mJ pulses) in which an input signal 113 cannot be guaranteed to provide sufficient intensity to prevent stored energy 7 and gain 8 building up in the gain medium 6 to values below those at which the stored energy 7 if released spontaneously will cause damage. In this event, it is essential to provide an energy limiting means 2 to prevent damage to the amplifier 110 or 120. Circumstances in which an input signal 113 might be absent include power-on and power-off modes, power interruption, cable disconnection, and testing subassemblies during manufacture.

Figure 13 shows apparatus in the form of a master oscillator power amplifier MOPA 130 comprising a seed laser 131, the optical isolator 102, and a power amplifier 133. The seed laser 131 can be the Q-switched lasers 20 or 90, and the power amplifier 133 can be the amplifiers 110 or 120. Alternatively the seed laser 131 can be a semiconductor laser, a distributed feedback laser, a distributed Bragg reflector laser, or a fibre laser. At least one of the seed laser 131 and power amplifier 133 contains the energy limiting means 2. The apparatus may include multiple power amplifiers 133 arranged in parallel, configured such that each amplifies the signal 113 from the seed laser 131.

Figure 14 shows apparatus in the form of a material processing system 140 comprising a plurality of seed lasers 131, a multiplexer 142, a first amplifier 143, a power amplifier 144, a demultiplexer 145, a plurality of scanners 146, a detector 147, and control circuitry 148. The seed lasers 131 can emit at the same wavelength or at different wavelengths. The apparatus is shown with seed lasers 131 emitting at

different wavelengths, their output powers being combined by the multiplexer 142 which can be a wavelength division multiplexer, and the combined signal being amplified by the first amplifier 143 and the power amplifier 144. At least one of the first and power amplifiers 143, 144 can be the amplifiers 110 or 120. The output from the power amplifier 144 is demultiplexed by the demultiplexer 145 which can be a bulk optic grating separating the different wavelengths to different scanners 146 which direct energy 141 to work pieces 1410. Depending upon the configuration of the apparatus, there may be a clamping signal 1411 (eg the energy limiting signal 29 of Figure 2) used to limit the output power of a component within the apparatus. This can be filtered out by an optical filter such as the demultiplexer 145 as shown. The apparatus can include the controller 148 to control the signals from the seed lasers 131 in synchronism with the scanners 146. This is especially useful in high-throughput laser marking systems in which the same mark is applied to many similar items. Optical feedback can be provided with an optical tap 149 and a detector 147. The optical tap 149 can comprise a beam splitter. Preferably, the optical tap 149 provides information about each wavelength in the system. Alternatively or in addition, there can be provided a plurality of optical taps 149 (not shown) located between the demultiplexer 145 and each scanner 146 in order to provide information on each wavelength. The controller 148 may also be used to shape the optical radiation 3 to a desired temporal characteristic 1414 such as a waveform 1412 with substantially rectangular pulses 1413. The detector 147 may be used to feed back the shape of the optical radiation 3 to the controller 148, useful for example for real-time control.

Examples of the apparatus have been described with reference to optical fibre amplifiers. These examples can be applied to lasers and amplifiers generally such as

diode-pumped solid state lasers, semiconductor lasers, waveguide lasers, and planar-waveguide lasers. The apparatus can include lasers that output in a single spatial mode or in a plurality of spatial modes. The apparatus shown with reference to Figure 14 can be used with a single scanner, and can comprise a single laser of the form shown with reference to Figures 1 to 13.

Figure 15 shows a master oscillator power amplifier 150 comprising a ytterbium-doped cladding pumped amplifier 151 and a seed laser 131. The gain medium 6 is the ytterbium-doped fibre 152 which is pumped by between 0W and 10W of pump power P_p 153 at a pump wavelength λ_p 154 of 915nm. The pump 5 comprises a plurality of single-emitting laser diodes. The energy limiting means 2 comprises first and second fibre Bragg gratings 155, 156 reflecting at an energy limiting wavelength λ_l 285 of 1110nm and with a first reflectivity R_1 157 of 5% and a second reflectivity R_2 158 of 5%. The amplifier 151 is driven from a seed laser 131 which in this example was a distributed feedback fibre laser emitting an input signal 113 with input signal power P_s 1510 of 7mW at a signal wavelength λ_s 4 of 1060nm.

When the ytterbium-doped fibre 152 is pumped, the energy limiting means 2 emits an energy limiting signal 29. An optional output filter 1515 is shown for removing the energy limiting signal 29 from the optical radiation 3. The output filter 1515 can be an optical filter, a grating, a long-period grating, or a fibre Bragg blazed grating.

Figure 16 shows the measured gain 161 of the amplifier 151 with increasing pump power P_p 153. The gain 161 is defined as the power ratio of the output radiation 3 at the signal wavelength λ_s 4 to the input signal power P_s 1510. The gain 161 increases with pump power 153 and rolls off at a maximum gain 165 of around 20dB. Experimentally it has been determined that no self Q-switching occurs in the

amplifier 151. In contrast, self Q-switching was evidenced in the amplifier 151 when the first and second fibre Bragg gratings 155, 156 were not provided, the ytterbium-doped fibre 152 failing owing to voids appearing in its core. This is an example of how the energy limiting means 2 comprising the first and second reflectors 281, 282 is limiting the gain 161 available for amplifying the input signal 113 when the ytterbium-doped fibre 152 is pumped by the pump 5 such that the stored energy 7 is unable to cause damage to the master oscillator power amplifier 150.

The optical radiation 3 emitted by the amplifier 151 of Figure 15 was measured in an optical spectrum analyser without the filter 1515 in place. Figure 17 shows the measured optical power spectra 171, 172 versus wavelength 174 measured with zero pump power 153 and 2.8W of pump power 153 respectively. The optical spectrum 171 reveals a signal component 175 at the signal wavelength λ_s 4. The optical spectrum 172 reveals a signal component 176 at the signal wavelength λ_s 4 and a signal component 177 at the energy limiting wavelength λ_1 285. The purpose of the filter 1515 shown in Figure 15 is to filter out the signal component 177 emitted by the amplifier 151.

The amplifier 151 of Figure 15 was modified by exchanging the first and second gratings 155, 156 with gratings having different reflectivities. The gain 161 was measured as a function of pump power 153. Figure 18 shows the gain 181 for 0% reflectivity gratings (ie the gratings were not present), the gain 182 for 3% reflectivity gratings, the gain 183 for 5% reflectivity gratings, and the gain 184 for 15% reflectivity gratings as a function of the pump power 153. The reflectivities referred to here are the first and second reflectivities 157, 158 which in this example are equal. The gain 161 is seen to reduce with increasing reflectivity. Such experimental measurements can be used to determine the reflectivities of the first and

second gratings 157, 158 required for a desired gain 161. It will be noted that no measurement results are shown for the case where no gratings were present for pump powers 153 greater than around 3.5W. No catastrophic failures have been seen with the amplifier 151 and similar amplifiers in which the gain 161 has been limited to around 30 to 35dB.

The first and second reflectivities 157, 158 need not be equal. Advantageously, the first reflectivity 157 can be greater than the second reflectivity 158. Such an arrangement will tend to emit the energy limiting signal 29 away from the seed source 131 and may remove the need for an isolator separating the seed source 131 from the amplifier 151. Alternatively, it may be advantageous to make the second reflectivity 158 greater than the first reflectivity 157. This will reduce the amount of energy limiting signal 29 emitted in the same direction as the optical radiation 3, and if the second reflectivity is greater than 90%, and preferably greater than 99%, may remove the need for the optical filter 1515.

From Figure 18, it is believed that the reflectivity for at least one of the first and second reflectors 155, 156 should be at least 0.01% (corresponding to at least 0.01% of optical radiation being reflected at the energy limiting wavelength 285).

Figure 19 shows a graph of the amplified spontaneous emission 191 measured as a function of wavelength 174 for the amplifier 151 without the first and second gratings 155, 156 and output filter 1515 in place. The amplified spontaneous emission 191 is shown for various levels of pump power 153 between 0.642W and 3.4W, the higher the pump power 153, the greater the amplified spontaneous emission 191.

Figure 20 shows the data of Figure 19 replotted as the double-pass (or round trip) small signal gain 201 of the gain medium 6 (ie not including the reflectivities).

These data were generated by doubling the values in dB indicated at each wavelength 174 in Figure 19 and then adding a constant gain in order to normalize the values to a measured gain at a fixed wavelength. Also shown is the product 209 of the first and second reflectivities R_1, R_2 158, 159 required to achieve a round-trip gain (not shown) through the amplifier 151 of unity. Unity round-trip gain 208 (not shown) corresponds to the onset of lasing. For example, a double pass gain 201 of 60dB corresponds to an (intensity) gain of 10^6. The product R1.R2 209 therefore needs to be 10^{-6} in order to achieve a round-trip gain 208 of unity.

Three example desired gains 202, 203, 204 are shown at a signal wavelength of 1060nm and are indicated in Figure 20 by the square 202, triangle 203 and circle 204 respectively. If an energy limiting wavelength λ_l 285 of 1110nm is selected, the required grating reflectivity products R1.R2 209 can be found by extrapolating along the gain curves 201 to arrive the energy limiting wavelength λ_l 285 of 1110nm and reading off the grating reflectivity product R1.R2 209. In this example, these are indicated by the square 205, triangle 206 and circle 207. As can be seen, the required grating reflectivity products R1.R2 209 is equal to the reciprocal of twice the small signal gain 8 at the energy limiting wavelength 285.

The square 202 corresponds to a desired gain 161 of 10dB at the signal wavelength λ_s 4 (half the double pass gain 201 of 20dB). The corresponding small signal gain 161 at the energy limiting wavelength λ_l 285 is found by extrapolating along the gain curves 201 to the square 205. Figure 20 shows that in order to achieve the desired gain 161 of 10dB at the signal wavelength 4, the grating reflectivity products R1.R2 209 at the energy limiting wavelength λ_l 285 of 1110nm indicated by the square 205 needs to be 2.5 x 10^{-2}. The grating reflectivity product R1.R2 209 is equal to the reciprocal of twice the small signal gain 161 at the energy limiting

wavelength λ_l 285. This product can be achieved by first and second reflectivities 157, 158 both equal to 16%. Referring to Figure 18, the gain 184 indicated by the squares was achieved with first and second grating reflectivities 157, 158 of 15% and resulted in the gain 161 being clamped at around 10dB.

Referring to Figure 20, the triangle 203 corresponds to a desired gain 161 of 19dB at the signal wavelength λ_s 4 (half the double pass gain 201 of 38dB). The corresponding small signal gain 161 at the energy limiting wavelength λ_l 285 is found by extrapolating along the gain curves 201 to the triangle 206. The grating reflectivity product R1.R2 209 at the energy limiting wavelength λ_l 285 of 1110nm indicated by the triangle 206 needs to be 2.5×10^{-3} which is equal to the reciprocal of twice the small signal gain 161 at the energy limiting wavelength λ_l 285. The product 209 can be achieved by first and second reflectivities 157, 158 both equal to 5%. Referring to Figure 18, the gain 183 indicated by the triangles was achieved with first and second grating reflectivities 157, 158 of 5% and resulted in the gain 161 of the amplifier 151 being clamped at around 20dB at the signal wavelength λ_s 4.

Referring to Figure 20, the circle 204 corresponds to a desired gain 161 of 22dB at the signal wavelength λ_s 4 (half the double pass gain 201 of 44dB). The corresponding small signal gain 161 at the energy limiting wavelength λ_l 285 is found by extrapolating along the gain curves 201 to the circle 207. The grating reflectivity products R1.R2 209 at the energy limiting wavelength λ_l 285 of 1110nm indicated by the circle 207 needs to be 8×10^{-4} which is equal to the reciprocal of twice the small signal gain 161 at the energy limiting wavelength λ_l 285. The product 209 can be achieved by first and second reflectivities 157, 158 both equal to 2.8%. Referring to Figure 18, the gain 182 indicated by the circles was achieved with first and second

grating reflectivities 157, 158 of 3% and resulted in the gain 161 of the amplifier 151 being clamped at around 25dB.

With reference to Figure 20, it is seen that if the gain medium 6 when pumped by the pump radiation 15 has a desired gain 161 at the signal wavelength λ_s 4, and a corresponding small signal gain 161 at the energy limiting wavelength λ_l 285, then the product 209 of the first and second reflectivities 157, 158 should be substantially equal to the reciprocal of twice the small signal gain 161 at the energy limiting wavelength λ_l 285.

The desired gain 161 at the signal wavelength λ_s 4 should be chosen to minimize the likelihood of damage to the amplifier 151. This is achieved by limiting the corresponding small signal gain 161 at the wavelength at which the small signal gain 161 peaks. With reference to Figure 20, the corresponding small signal gain 161 to the circle 204 is shown by the cross 208, which corresponds to twice the maximum gain 14 of at the maximum gain wavelength 18 of 1076nm (the factor of 2 occurs because Figure 20 shows the double pass small signal gain 201).

If the gain medium is pumped by at least 1W of the pump radiation 15, then it is desirable that the maximum gain 14 at the maximum gain wavelength 18 is less than 40dB. This is to prevent optical damage from occurring. In this example, the product 209 of the first and second reflectivities 157, 158 would be approximately 10^{-4} at 1110nm.

If the gain medium is pumped by at least 10W of the pump radiation 15, then it is desirable that the maximum gain 14 at the maximum gain wavelength 18 is less than 30dB. In this example, the product 209 of the first and second reflectivities 157, 158 would be approximately 5×10^{-4} at 1110nm.

If the gain medium is pumped by at least 100W of the pump radiation 15, then it is desirable that the maximum gain 14 at the maximum gain wavelength 18 is less than 25dB. In this example, the product 209 of the first and second reflectivities 157, 158 would be approximately 10^{-3} at 1110nm.

If the gain medium is pumped by at least 1000W of the pump radiation, then it is desirable that the maximum gain 14 at the maximum gain wavelength 18 is less than 20dB. In this example, the product 209 of the first and second reflectivities 157, 158 would be approximately 5×10^{-3} at 1110nm.

The above are general guidelines that have been found useful for cladding pumped amplifiers. However, the strength of the first and second reflectivities 157, 158 required in any particular embodiment is dependent upon the amount of pump radiation 15 delivered to the gain medium 6 and also upon the spectroscopy of the gain medium 6. It is therefore sensible to optimise the first and second reflectivities 157, 158 experimentally.

Figures 21 to 26 show modelling results for the amplifier 121 shown with reference to Figure 12, in which the energy limiting means 2 is provided by the energy limiting power 94 supplied by the energy limiting source 91. The modelling results are for a rare-earth doped fibre 23 doped with ytterbium. Figure 21 shows the small signal gain 211 for zero energy limiting power 94, and the small signal gain 212 for 8.4mW of energy limiting power 94 at an energy limiting wavelength λ_l 285 of 1110nm. The pump power P_p 153 delivered to the rare-earth doped fibre 23 by the pumps 5 was 4W (in total), and was at a pump wavelength λ_p 154 of 915nm. The small signal gains 211 and 212 are plotted as a function of the signal input power 115 at a signal wavelength λ_s 4 of 1060nm. The gain 211 is seen to increase with reducing signal input power 115. Eventually the gain 211 will be limited by the

amount of pump power P_p 153 and by amplified spontaneous emission that is emitted by the rare-earth doped fibre 23.

Figure 22 shows the small signal gain 221 as a function of wavelength 174 for the amplifier 121 that has been clamped with 8.5mW of energy limiting power 94. The small signal gain 222 at the energy limiting wavelength λ_l 285 of 1110nm is approximately 3dB less than the small signal gain 212 at the signal wavelength λ_s 4. The small signal gain 212 is approximately 8dB less than the maximum gain 14. A differential gain 223 equal to the maximum gain 14 (at the maximum gain wavelength 18) minus the small signal gain 212 can be defined as shown in Figure 22. The differential gain 223 is 8dB, that is, the amplifier 121 can provide an additional 8dB gain over and above the gain 211 and 212 shown in Figure 21.

Referring to Figure 21, the gain 211 of 40dB at the signal wavelength λ_s 4 corresponds to maximum gain 14 at the maximum gain wavelength 18 of 48dB, and as can be seen, the gain 211 is rising with reducing signal input power 115. A maximum gain 14 of 48dB is capable of generating an unwanted pulse that could damage optical components within the amplifier 121. Such pulses have been been experienced with pump diodes breaking, and also catastrophic failure of optical fibres, even at relatively low pump powers of 1W. The energy limiting power 94 of 8.5mW clamps the gain 212 at approximately 25dB for low signal input powers 115. The gain 212 of 25dB at the signal wavelength λ_s 4 together with the differential gain 223 of 8dB corresponds to a maximum gain 14 of 33dB at the maximum gain wavelength 18. The energy limiting power 94 reduces the amount of stored energy 7 that can be stored by the rare-earth doped fibre 23, and thus ensures that the gain medium 6 is unable to release the stored energy 7 at a level that would damage the amplifier 121.

Figure 23 shows the small signal gain 231 for zero energy limiting power 94, and the small signal gain 232 for 200mW of energy limiting power 94 at an energy limiting wavelength λ_l 285 of 1082nm. The pump power P_p 153 delivered to the rare-earth doped fibre 23 by the pumps 5 was 40W (in total), and was at a pump wavelength λ_p 154 of 915nm. The small signal gains 231 and 232 are plotted as a function of the signal input power 115 at a signal wavelength λ_s 4 of 1094nm. The gain 231 is seen to increase with reducing signal input power 115, which makes the amplifier 121 susceptible to damage by release of the stored energy 7. The gain 232 is clamped to 23dB at low signal input powers 115.

Figure 24 shows the corresponding small signal gain 241 as a function of wavelength 174 for the amplifier 121 that has been clamped with 200mW of energy limiting power 94. The signal wavelength λ_s 4 corresponds to the maximum gain wavelength 18 since the gain 241 is a maximum at the signal wavelength λ_s 4. The differential gain 223, defined with reference to Figure 22, is therefore zero. Referring to Figure 23, the energy limiting power 94 reduces the amount of stored energy 7 that can be stored by the rare-earth doped fibre 23, and thus ensures that the gain medium 6 is unable to release the stored energy 7 at a level that would damage the amplifier 121.

Figure 25 shows the small signal gain 251 for zero energy limiting power 94, and the small signal gain 252 for 7W of energy limiting power 94 at an energy limiting wavelength λ_l 285 of 1104nm. The pump power P_p 153 delivered to the rare-earth doped fibre 23 by the pumps 5 was 400W (in total), and was at a pump wavelength λ_p 154 of 915nm. The small signal gains 251 and 252 are plotted as a function of the signal input power 115 at a signal wavelength λ_s 4 of 1094nm. The gain 251 is seen to increase with reducing signal input power 115, which makes the

amplifier 121 susceptible to damage by release of the stored energy 7. The gain 232 is clamped to 16dB at low signal input powers 115.

Figure 26 shows the corresponding small signal gain 261 as a function of wavelength 174 for the amplifier 121 that has been clamped with 7W of energy limiting power 94. The signal wavelength λ_s 4 is 3nm less than the maximum gain wavelength 18. The gain 252 is approximately the same as the maximum gain 14. The differential gain 223, defined with reference to Figure 22, is approximately zero. Note that the differential gain 223 is approximately zero provided that the signal wavelength λ_s 4 is within 10nm of the maximum gain wavelength 18. Referring to Figure 25, the energy limiting power 94 reduces the amount of stored energy 7 that can be stored by the rare-earth doped fibre 23, and thus ensures that the gain medium 6 is unable to release the stored energy 7 at a level that would damage the amplifier 121.

Referring to Figure 1, 9 and 12, it is preferable for a gain medium 6 that is pumped with at least 1W of pump power P_p 153 (where problems are first encountered with ytterbium-doped fibre lasers), that the energy limiting source 91 should provide at an energy limiting wavelength 285 an energy limiting power 94 greater than -40dB relative to the pump power 153. The energy limiting power 94 acts on the gain medium 6 to reduce the amount of stored energy 7 and gain 8 when the gain medium 6 is pumped by the pump 5 such that the stored energy 7 is unable to cause damage to the apparatus 10. The energy limiting power 94 has been referenced to the pump power 153 and values selected assuming that the energy limiting wavelength 285 is close to the maximum gain wavelength 18.

If the gain medium 6 is pumped by at least 10W of the pump power P_p 153, then it is preferable that the energy limiting source 91 provides an energy limiting power 94 greater than -30dB relative to the pump power P_p 153.

If the gain medium is pumped by at least 100W of the pump power P_p 153, then it is preferable that the energy limiting source 91 provides an energy limiting power 94 greater than -25dB relative to the pump power P_p 153.

If the gain medium is pumped by at least 1000W of the pump power P_p 153, then it is preferable that the energy limiting source 91 provides an energy limiting power 94 greater than -20dB relative to the pump power P_p 153.

In the above four examples (corresponding to pump powers P_p 153 of greater than 1W, 10W, 100W, and 1000W), the energy limiting power 94 should be increased as the energy limiting wavelength 285 moves away from the maximum gain wavelength 18 by a factor corresponding to the difference in the maximum gain 14 and gain 8 of the gain medium 6 at the energy limiting wavelength 285.

Experimental optimisation of these energy limiting power 94 and energy limiting wavelength 285 is advisable. If optical damage (particularly of pumps, fibres and other optical devices) is experienced, then the energy limiting power 94 should be increased.

With reference to the embodiments described in Figures 1 to 26, the energy limiting wavelength 285 can be in the same emission band 9 as the signal wavelength 4.

Alternatively, the energy limiting wavelength 285 can be in a different emission band 9 from the signal wavelength 4. For example with erbium-ytterbium dopants, the gain medium 6 can be clamped in the lower emission band (from around 970nm to 1150nm, but preferably between 1070nm to 1150nm) and the signal

wavelength 4 can be in higher emission band (from around 1530nm to 1600nm). Clamping in the lower emission band is advantageous because the ytterbium dopant has faster dynamics.

Alternatively, the gain medium 6 can be clamped in the higher emission band (from around 1530 to 1600nm) and the signal wavelength 4 can be in the lower emission band (from around 970nm to 1150nm, but preferably between 1070nm to 1150nm). The latter alternative is attractive because it offers the benefits of increased reliability that accrue from the energy limiting means 2, yet when the input signal is present, the effect of the energy limiting means 2 on the signal will be less significant as the energy limiting means 2 is operating on a different dopant (the erbium). Advantages include better efficiency and transient behaviour.

Advantages of having the energy limiting wavelength 285 greater than the signal wavelength 4 include less reabsorption at the energy limiting wavelength 285. This implies that lower energy limiting powers 94 or first and second reflectivities 157, 158 can be used to clamp the gain medium 6. In addition, the transient behaviour of amplifiers and lasers may be better (for example the Q-switched laser of Figure 2).

The energy limiting wavelength 285 can be less than the signal wavelength 4. This may have advantages if more than one energy signal wavelength 285 were used, for example one greater and one less than the signal wavelength 4.

Preferably, the energy limiting wavelength 285 and the maximum gain wavelength 18 are separated by less than 10nm in order that less energy limiting power 94 can be used. Alternatively, it can be advantageous to have the energy limiting wavelength 285 and the maximum gain wavelength 18 separated by more

than 10nm in order to facilitate filtering out optical radiation at the energy limiting wavelength 285 using optical filters 1515.

Although much of the discussion pertaining to Figures 2, 9, 11, 12 and 15 have centred on ytterbium, the rare-earth doped fibre 23 may be core pumped, or may be a cladding pumped optical fibre comprising a core, an inner cladding for guiding pump radiation supplied by the pump, and an outer cladding, and in which the rare earth dopant is disposed in at least one of the core and the inner cladding. The rare-earth dopant may be selected from the group comprising ytterbium, erbium, neodymium, praseodymium, thulium, samarium, holmium and dysprosium, erbium codoped with ytterbium, or neodymium codoped with ytterbium. The invention also extends to alternative gain media 6, for example crystals in rod and disk form.

It is to be appreciated that the embodiments of the invention described above with reference to the accompanying drawings have been given by way of example only and that modifications and additional components may be provided to enhance performance. In addition, the invention can be considered to be an amplifier, a laser, a master oscillator power amplifier, a Q-switched laser, a source of amplified spontaneous emission, or a continuous wave laser. The invention can also considered to be a laser for material processing.

The present invention extends to the above-mentioned features taken in isolation or in any combination.